VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

BRNO UNIVERSITY OF TECHNOLOGY

FAKULTA ELEKTROTECHNIKY A KOMUNIKAČNÍCH TECHNOLOGIÍ

FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION

ÚSTAV JAZYKŮ

DEPARTMENT OF FOREIGN LANGUAGES

VYUŽITÍ 3D TISKÁREN V MEDICÍNĚ

THE USE OF 3D PRINTERS IN MEDICINE

BAKALÁŘSKÁ PRÁCE

BACHELOR'S THESIS

AUTOR PRÁCE Vladislav Shchennikov

AUTHOR

VEDOUCÍ PRÁCE Mgr. Magdalena Šedrlová

SUPERVISOR

BRNO 2019

VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ
FAKULTA ELEKTROTECHNIKY A KOMUNIKAČNÍCH TECHNOLOGIÍ

Bakalářská práce

bakalářský studijní obor **Angličtina v elektrotechnice a informatice**
Ústav jazyků

Student: Vladislav Shchennikov ***ID:*** 197694
Ročník: 3 ***Akademický rok:*** 2018/19

NÁZEV TÉMATU:

Využití 3D tiskáren v medicíně

POKYNY PRO VYPRACOVÁNÍ:

Cílem práce je představit technologii 3D tiskáren a varianty jejich využití pro lékařské účely.

DOPORUČENÁ LITERATURA:

Dle pokynů odborného konzultanta

Termín zadání: 4.2.2019 ***Termín odevzdání:*** 28.5.2019

Vedoucí práce: Mgr. Magdalena Šedrlová
Konzultant:

doc. PhDr. Milena Krhutová, Ph.D.
předseda oborové rady

Abstrakt

Text se zabývá rychlým rozvojem trojrozměrných tiskáren, popsáním jejich obecných komponentů a využitím 3D tiskáren v medicíně. V našem současném světě se v poslední době objevily 3D tiskárny a byly okamžitě použity v různých oborech a průmyslech. 3D tisk je inovační a perspektivní technologie, která nepředstavitelně mění lidské životy a zkrátí obrovské množství času a zdroje, které se vynakládají na vytváření určitých produktů. V této bakalářské práce uvedené příležitosti využití těchto technologií v různých oblastech především v medicíně, stejně jako rozdíly mezi jednotlivými technologiemi a jejimi výhody a nevýhody.

Klíčová slova

Trojrozměrná tiskárna, technologie 3D tisku, provoz, průmysl, zdroje, medicína.

Abstract

The text deals with the rapid development of three-dimensional printers, description of their general components, and the utilization of 3D printers in medicine. In our contemporary world, three-dimensional printers have appeared more recently and immediately were applied in various fields and industries. 3D printing is an innovative and forward-looking technology that will unimaginably change people's lives and will reduce an enormous amount of time and resources, that is spent on creating certain products. The opportunity of using such technology in different areas, particularly in medicine are described in this bachelor thesis, as well as the differences between individual technologies and their advantages and disadvantages.

Keywords

Three-dimensional printer, 3D printing technology, operation, industry, resources, medicine.

SHCHENNIKOV, V. Využití 3D tiskáren v medicíně. Brno: Vysoké učení technické v Brně, Fakulta elektrotechniky a komunikačních technologií, 2019. 44 s. Vedoucí práce Mgr. Magdalena Šedrlová.

Prohlášení

Prohlašuji, že svoji bakalářskou práci na téma: "Využití 3D tiskáren v medicíně" jsem vypracoval samostatně pod vedením vedoucí bakalářské práce a s použitím odborné literatury a dalších informačních zdrojů, které jsou všechny citovány v práci a uvedeny v seznamu literatury na konci práce. Jako autor uvedené bakalářské práce dále prohlašuji, že v souvislosti s vytvořením této bakalářské práce jsem neporušil autorská práva třetích osob, zejména jsem nezasáhl nedovoleným způsobem do cizíchautorských práv osobnostních a/nebo majetkových a jsem si plně vědom následků porušení ustanovení § 11 a následujících zákona č. 121/2000 Sb., o právu autorském, o právech souvisejících s právem autorským a o změně některých zákonů (autorský zákon), ve znění pozdějších předpisů, včetně možných trestněprávních důsledků vyplývajících z ustanovení části druhé, hlavy VI. díl 4 Trestního zákoníku č. 40/2009 Sb.

V Brně dne: ………………………………

Vladislav Shchennikov

ACKNOWLEDGEMENTS

I would like to thank my supervisor, Mgr. Magdalena Šedrlová from the department of Foreign Languages for patience, professionalism, and guiding me during writing this thesis. Furthermore, I would like to thank my parents and the closest friends for supporting me.

Table of contents

1 INTRODUCTION

Three-dimensional printing is one of the latest innovative technologies that made a breakthrough in engineering, manufacturing, and information technology and has every chance to revolutionize medicine incredibly. What a decade ago seemed impossible and beyond our understanding now is getting in everyday practice. The 3D printing revolution transforms our life. While traditional printers operate only with paper, 3D printers construct objects from plastic, metal, glass, and even from cells. An example of visual representation of the three-dimensional printer "Makerbot Replicator (5th generation)" is shown in Figure 1.

A jeweler could print rings, earrings, medallions to utilize as layers for future products. An inventor could use a 3D printer to create an inexpensive prototype of a handle for a new screwdriver, testing it in plastic first to ensure himself that the design feels appropriate. A robotics hobbyist might find a 3D printer helpful for producing small gears or wheels unique in size or shape, that cannot be offered in usual markets.

What about medicine? Nowadays, right before our eyes, there is a revolution in the field of medicine. Scientists from all over the world use 3D printers to print organs, tissues, and implants for people with various diseases and injuries. Printing in medicine is a more reliable, cheaper, and faster solution than outdated traditional methods. With each passing day, progress is being made, research is being conducted, and trials are being conducted to provide a broader range of services to patients seeking of treatment and organ transplants.

Moreover, it is just a beginning, and it is hard to imagine what 3D printer will "build" in the next decades.

Figure 1 An example of 3D printer "Makerbot Replicator 5th generation" (retrieved from https://www.3dhubs.com/3d-printers/makerbot-replicator-5th-gen)

2 OPERATION OF 3D PRINTER

2.1 Definition of 3D printing

The 3D printing technology can be described as advanced manufacturing using a series of overlapping layers to create an object with the help of a computer program.

Dr. Kalaskar from Institute of Orthopaedics and Musculoskeletal Science defines 3D printing as:

"*Additive manufacturing or rapid prototyping or layered manufacturing. Conversely, 3D printing is a generic term that describes various methods of constructing objects in a layer-by-layer fashion. The object to be printed is created using computer-aided- design software package which is then exported as a file to be printed. The exported file splits the 3D object into a series of layers—the object is then printed layer by layer. The technology involves printing a single material or a combination of multiple materials in a layer-by-layer manner, regulating the shape of every individual layer, eventually resulting in a complex 3D structure with limited restrictions on its spatial arrangement*" (1).

2.2 Process of operation

The personal 3D printers people use at present often construct things from plastic using an approach called fused filament fabrication. Brian Evans describes this process as follows: *"Plastic filament is heated and extruded from a nozzle like a tiny and precise hot glue gun while the machine draws out 3D objects layer by layer. As one layer of plastic is laid on top of another, they fuse together, and, when cooled, form a solid and durable plastic part."* (1). This innovation is utilized in the design and engineering industries for everything, beginning with designing parts for machines.

2.3 Parts of 3D printer

In order to sufficiently understand how three-dimensional printers work, it is necessary to examine its essential parts.

2.3.1 Extruder

One of the most complex parts of a 3D printer is extruder. Figure 2 shows a complete extruder with filament driver and hot end. An extruder consists of two key elements: the filament drive and the thermal hot end.

An extruder is capable of laying down thin strands of thermoplastic—a type of plastic that will soften to a semiliquid state when heated. Extruder usually utilizes a geared arrangement to permit the stepper motor to apply more torque to the filament and to overcome forces like the tension of the spool or the weight and thickness of the filament. (Evans 3).

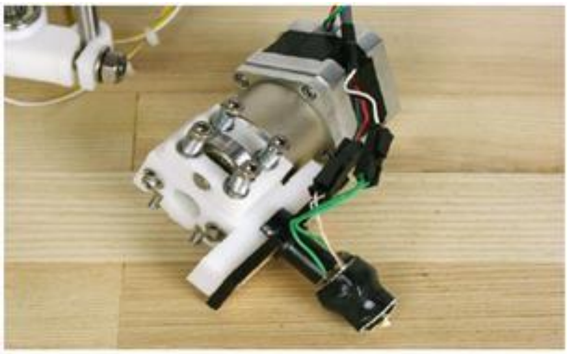

Figure 2 An example of the layout of the extruder and a spool of filament. Adopted from Evans (2012) "Practical 3D Printers."

Figure 3 illustrates a layout of the extruder and a spool of filament. The fiber is brought into the extruder (cold end) and after that pushed into the nozzle (hot end). When the plastic reaches the hot end, it is heated at about 200°C. When the filament is heated enough, it is extruded onto a flat surface, that used as the foundation for the object. Generally, the outer sides of an object are printed before the interior edges. At that point, the interior of the layer is printed as a solid layer. The heated extrusion is colder than the filament from the spool because the nozzle has a microscopic slot ranging average of 0,4 millimeters. (Bell 6). To facilitate understanding the representation of how the layer is built from various lines of heated fiber is demonstrated in Figure 3.

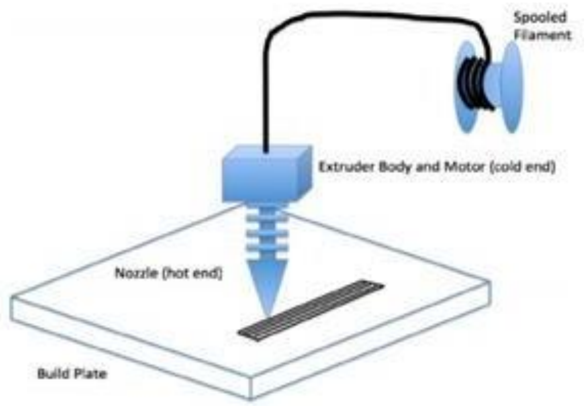

Figure 3. Fused Filament Fabrication extrusion with nomenclature. Adopted from Bell (2014) "Maintaining and troubleshooting your 3D printer."

2.3.2 Printbed

A printbed is one of the most critical parts of a 3D printer, and it is the surface of a 3D printer where 3D objects are built. A printbed must be flat and smooth in order to form proportional layers. The size of a printbed may significantly vary and depends on the type of the printer. Figure 4 shows a heated printbed that some three-dimensional printers have either as standard or as an option. The printbed is utilized to avert the breaking of prints as they cool and to make better attachment between the first layers of the print and the printbed surface. The material of the printbed may differ.

Typically, it is made from aluminum or glass in order to spread the warmth across space and to create a level surface. These materials have their benefits, for instance:

"Glass provides the smoothest surface to print on while aluminum conducts heat better for a heated platform. To prevent the object from lifting off the surface in midprint, these surfaces are often covered in one kind of tape or another to provide a surface that is inexpensive to replace periodically. These materials include Kapton or polyimide tape, PET (polyethylene terephthalate) or polyester silicon tape, or even

hardware store–variety blue painter's tape, depending on the type of filament used." (Evans 4).

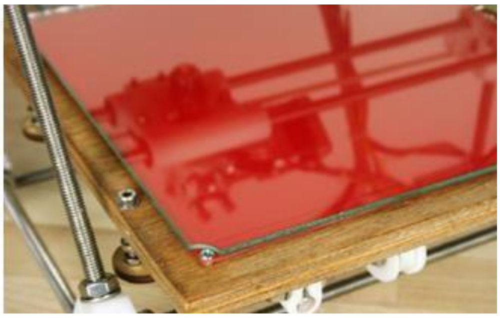

Figure 4. Heated printbed. Adopted from Evans (2012) "Practical 3D Printers."

2.3.3 Mechanical endstops

Figure 5 represents the mechanical endstops where the length of movement for every linear axis is limited. Endstops have switches that can control the movement. For instance, when the endstops reach a limit in direction, switches prevent the motion by sending a command to the printer's controller electronics.

"*While endstops are not strictly needed for operation, having at the very least one endstop in the minimum position on each axis will allow the printer to home itself at the beginning of each print for repeatable and accurate prints every time."* (Evans 6).

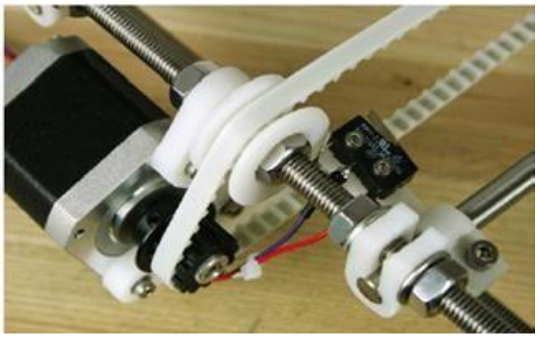

Figure 5. Mechanical endstops. Adopted from Evans (2012) "Practical 3D Printers."

2.3.4 Frame

The frame is responsible for holding everything together in the 3D printer. It forms the structural component of a 3D printer, and the ultimate precision of the printer depends on its material and construction. Various types of 3D printers have different designs of frames. One of them is a "RepRap" style design that uses 3D-printed components along with threaded rod to manufacture the frame. On the other hand, another type of 3D printer is a Box Bots model has the same properties as the MakerBot or the MakerGear Mosaic, represented on the Figure 6 and utilizes laser-cut plywood, the technology that bolts together the parts to make the frame.

One of the easiest and user-friendly type of frame is the one in which two pieces of plywood are held together with protrusions from one piece of plywood attached to the grooves in the other. This type of frame is a laser-cut plywood frame.

"A laser-cut plywood frame uses slot-and-tab construction, where two pieces of plywood are held together with tabs from one piece fitting into slots in the other, and connected with nuts and bolts. This type of frame is generally easier to assemble and offers better up-front precision, so that printer calibration is easier; however, these frames are often louder during operation, and all those screws will eventually need retightening later." (Evans 7).

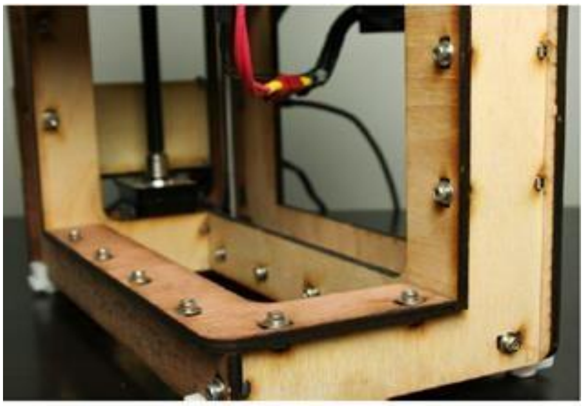

Figure 6. "MakerGear Mosaic" plywood frame. Adopted from Evans (2012) "Practical 3D Printers."

2.3.5 Cartesian robot

Cartesian robot plays a fundamental role in the operation of the 3D printer. A cartesian robot is a machine that moves in three different dimensions, along with the Cartesian coordinates. Such a machine can operate only with the assistance of small stepper motors that can move with high precision.

"All of the 3D printers use timing belts and pulleys along their x- and y-axes to provide fast yet accurate positioning, and most use threaded rod, or lead screws, to position the z-axis with even greater precision." (Evans 3).

Figure 7 represents the example of a cartesian coordinate robot that is numerically controlled by the computer software and arranges thermoplastic extruder along each of these linear axes layers upon layer.

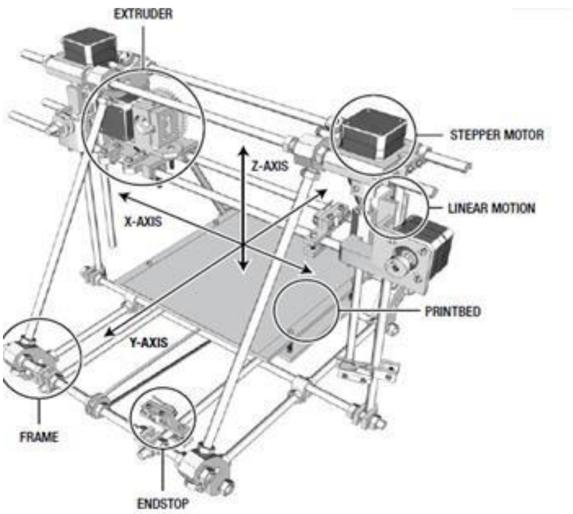

Figure 7. The basic structure of a cartesian coordinate robot. Adopted from Evans (2012) "Practical 3D Printers."

2.4 Linear motion

The properties of 3D printers such as accuracy, speed, and sustainability often determine a linear motion system. Linear motion system or mechanical assembly which oblige individual axis to act for a 3D printer is fundamental to supply a smooth, flat, and leveled motion of the payload for reproducing a real object from digital data.

"Most personal 3D printers use smooth, precision ground rods for each axis, and either plastic, bronze, or linear ball bearings to glide across each rod." (Evans 4).

Endurance and smooth operation of linear ball bearing systems earned an excellent reputation among the consumers. However, the main drawback of these systems is loud noise during operation. Figure 8 illustrates the example of self-aligning bronze bearings. Self-aligning bronze bearings take a bit more work to align during the process of constructing objects.

Each type of linear motion system is unique and depends on the person's requirements. Typically, 3D printed bushings are inexpensive, but their longevity is low. Machined plastic bushings are likely to deform under more massive utilization, but its smoothness allows to operate appropriately for the slow-moving z-axis.

"On the other hand, the reliability of linear bearings discussed earlier depends on the quality of the smooth rails they ride on, and they cost more. Other, more exotic materials, like felt, have also been tried with mixed results. Some printers even use industrial linear glides that have the potential for greater accuracy and longevity at increased cost and mechanical complexity." (Evans 5).

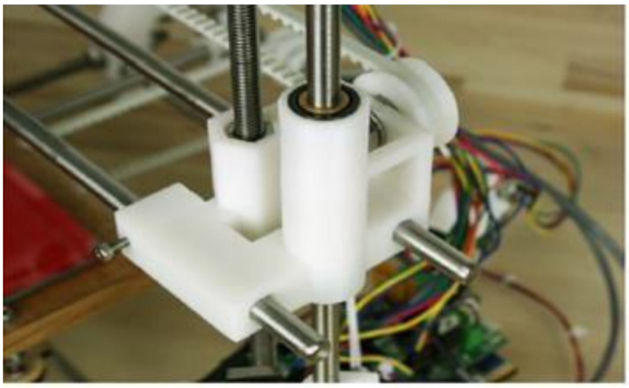

Figure 8. Self-aligning bronze bearings. Adopted from Evans (2012) "Practical 3D Printers."

3 DIFFERENCE BETWEEN INDIVIDUAL TECHNOLOGIES AND THEIR ADVANTAGES AND DISADVANTAGES

There are numerous approaches to adding the material in an additive fashion. Each layer is applied to the next layer until the object is completely printed. This can be done either by using the fusion method, which is done by layer-by-layer application of the molten material on the working platform, or by using laser radiation on the contours of the future object. Each technique varies in the methods in which layers are formed and printing materials used. A detailed overview of all technologies used in 3D printing is described below.

3.1 Resin-based systems

3.1.1 Stereolithography

Stereolithography (SLA) is the oldest method of 3D printing that is used nowadays. The origins of conventional 3D printing traced back to the 20th century. In 1980 the first 3D printing stereolithography (SLA) technology was invented by Charles Hull. It was the first commercial 3D printing project that uses a laser to construct various 3D objects within a tank of liquid photopolymer. The essence of this technology is that the tank is filled with liquid photopolymer, which is exposed to the laser radiation, layer by layer along the contours of the future object. Under the influence of radiation photopolymer resin hardens, gradually forming a finished product. Kalaskar describes this process as following:

"*Stereolithography is an additive manufacturing process in which photons from ultraviolet (UV) laser light source is targeted onto the surface of a photo-curable liquid monomer bath and scanned in different patterns. The scanned monomers are sensitive to light, hence can be crosslinked by using a suitable light source. When exposed to photons these monomers harden to form the required 2D cross-sections, while the unexposed monomers remain unchanged in the bath.*" (2).

Photopolymer is a substance that changes its properties under the influence of ultraviolet light. In a regular condition photopolymer flexible, and at hit under Uf-radiation of an electromagnetic range acquires durability. Duration of irradiation is calculated depending on the specific material and size of the object.

The next stage of creation of the object of this technology is a gradual covering of the following solid sites with a layer of liquid and so on until the product is completely done. The object layers are also dried in an adjustable furnace.

"After the first layer of the liquid resin is cured, the platform stage is lowered slightly, allowing a new layer of liquid to cover the now-solid planar sections. Once the planar sections are completed, the prototype is then post-cured in a controlled furnace, or an ultraviolet curing apparatus, for a designated period of time, to allow final polymerization." (Kalaskar 25)

A visual representation of the basic parts of the stereolithography machine is shown on the Figure 9.

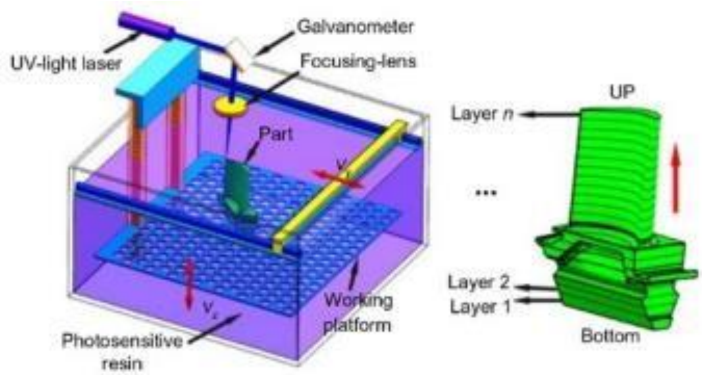

Figure 9. Basic parts of the stereolithography machine. Adopted from Kalaskar (2017) "3D printing in medicine."

"In SLA, control of the thickness of the cured layer is crucial for obtaining the optimal resolution. For a given resin, the cure depth is determined by the energy of the light to which the resin is exposed. This energy can be controlled by adjusting the power of the light source, and the scanning speed (for laser systems) or the exposure time (for projection systems)." (Kalaskar 25).

The Stereolithography constitutes a "gold standard" because the accuracy of such printing is much higher than other technologies, which has led to its popularity in certain areas. SLA is used in jewelry and dentistry due to the high level of detail of the products. However, it is more expensive and more labor-intensive concerning other 3D printing methods.

Another significant drawback of this technology is the amount of time spent on printing products. Depending on the size of the product, it can take from several hours to several days to print. The technology has many advantages, such as easy processing of the manufactured prototype, high quality of the constructed objects, and low noise level of production of details.

3.1.2 Microstereolithography

Improved stereolithography technology - MLA, designed to reduce the thickness of the layer further and speed up the production time of the object. This technology is used to create small and high-resolution nano parts for the automotive and aerospace industries. It has a similar principle of object constructing.

"With projection MSL, a dynamic pattern mask is created using an LCD (liquid crystal display) screen or DMD (digital micromirror device) chip and a light source shone through or across the mask onto the photopolymerizable resin, curing a patterned layer in a parallel fashion." (Kalaskar 26).

3.1.3 Digital light processing

The principle of operation of the digital light processing technology is analogous to SLA method with the only difference of the light source used to cure the resin instead of the laser. DLP is a type of vat polymerization. This means that conventional source of light from projectors starting to affect the vat of liquid. With the help of these rays, the required 3D model is cut out layer by layer from the vat and then hardens to the proper shape. According to think 3D.in:

"The 3D model is sent to the printer; a vat of liquid polymer is exposed to

light from a DLP projector under safelight conditions. The DLP projector displays the image of the 3D model onto the liquid polymer. The exposed liquid polymer hardens, and the build plate moves down, and the liquid polymer is once more exposed to light. The process is repeated until the 3D model is complete and the vat is drained of liquid, revealing the solidified model" [14]

The main advantage of this technology in comparison with Stereolithography is that the formation of the product is several times faster due to the arc lamp with a liquid crystal display. Details are obtained with the same high resolution as in SLA technique.

All3dp.com states that "*With SLA, the laser has to individually cure the resin in a "point to point" technique. On the other hand, a DLP projector screen flashes an image of a layer all at once. Thus, all points of a layer can be cured simultaneously. In this way, the print speed is increased in comparison to SLA since it takes less time to cure a single layer."* [7]

Figure 10 illustrates a schematic of the DLP based printer.

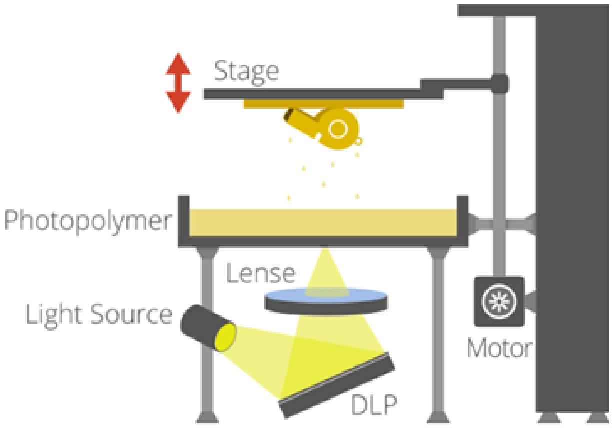

Figure 10. Scheme of the digital light processing printer. Adopted from think3d.in

Nevertheless, 3D printers using digital light processing technology have their limitations. Because of the digital screen, extensive details are more complicated to print, and the resolution of such objects is low. This drawback can be compared to the enlargement of the picture on the phone. The more the picture increases, the worse the quality, that is why DLP technology is not suitable for printing large objects.

3.2 Powder-based systems

3.2.1 Selective laser sintering

Selective laser sintering technology is one of the most popular techniques for manufacturing complex objects. SLS uses a CO_2 laser to fuse the powdered material. 3D printers based on such technology consist of laser, scanning system, chamber, powdered material, roller of leveler, and powder delivery system. A visual representation of such a system can be seen in figure 11.

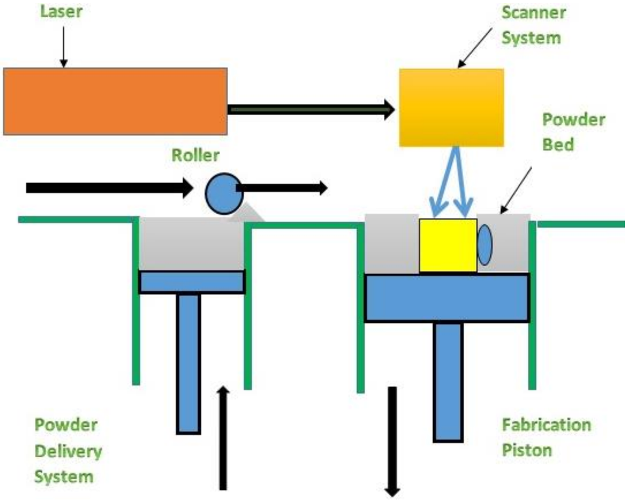

Figure 11. Scheme of the selective laser sintering process. Retrieved from manufactur3dmag.com

As it was mentioned before, the SLS uses a laser that passes through the scanning system and then heats the powdered material particles with high precision, which are soldered together to form a layer of the right shape. The laser then heats the particles of the second layer by fusing it in the same way with the first layer. As a result, layer upon layer the desired figure is formed. Manufactur3dmag states that:

"*The process starts with the build chamber being heated just below the melting temperature of the powdered material. On reaching the preset temperature, the roller brings the first layer of material and spreads it in the build chamber. The powerful CO_2 laser is activated and falls on the scanning system. The scanning system directs the laser to the accurate coordinates and traces the desired geometry on the first layer of the material. As the laser falls on the fine particles, they are heated above its melting* *temperature, and adjacent particles fuse together to form a bond. This process is also called as Powder Bed Fusion or Sintering*." [10]

Also, it should be mentioned that the process is unique and distinguishes itself by the fact that the printing of the figure starts with the first lower layer from top to bottom, unlike other methods.

The main disadvantage of such technology is that the materials used in a powdered form must be heated during the whole process, which significantly affects its properties.

"Since the chamber must be filled with powder, the material is heated every time an object is printed. This affects the material properties, and after a specific number of times, the material loses its standard properties, and it cannot be reused again." [9]

However, Kalaskar highlights a number of advantages of this technology and materials used in powdered form:

"The major advantages of the SLS technology is the ability to process about any material in a powdered form: polymers, metals, ceramics and including a variety of composite materials such as glass reinforced polymers, metal/polymer composite, metal/metal composites. Moreover, SLS does not require the use of organic solvents and can be used to make intricate biphasic scaffold geometries at both the macro and micro scale. These possibilities have opened the way for many medical applications... such as HA-reinforced polyethylene composites for bioactive bone implants" (29).

3.2.2 Other powder-based technologies

There are plenty of other powder-based technologies such as direct metal laser sintering (DMLS), selective laser melting (SLM), and direct laser forming (DLF), that use the same concept as SLS except that material is not sintered but melted. Last but not least method of manufacturing objects is electron beam melting (EBM), which differs from other laser-based systems in that it uses a high-energy beam instead of a powerful laser. *"In contrast to laser-based systems, EBM uses a high-energy electron beam to induce fusion between metal powder particles. In the EBM process, a focused electron beam scans across a thin layer of pre-laid powder, causing localized melting and resolidification as per the slice cross-section."* (Gibson 26)

3.3 Extrusion-based system

The extrusion-based system is one of the most popular and contemporary methods of fabricating various parts by consistently squeezing the filament out of the extruder nozzle. Dr. Gibson from the National University of Singapore describes this method as:

"These technologies can be visualized as similar to cake icing, in that material contained in a reservoir is forced out through a nozzle when pressure is applied. If the pressure remains constant, then the resulting extruded material ... will flow at a constant rate and will remain a constant cross-sectional diameter. The material that is being extruded must be in a semi-solid state when it comes out of the nozzle." (143).

3.3.1 Fused Deposition Modeling

Fused deposition modeling (FDM) is the most frequently used extrusion-based technology nowadays was invented and patented by Scott Crump, the founder of the Stratasys company in 1992. Since then, the technology has started to develop and implement in every fields and industry with great speed. The principle of operation is simple: a spool of thermoplastic filament that is heated enough feeds into an FDM extrusion head. The computer-controlled head controls an exact outline of every cross-section layer of the part. The thermoplastic material is pressed out of the nozzle by a high-resolution pump. When the first layer is ready, the extrusion head starts to create the next layer by bonding the previous one. According to manufactur3dmag:

"A solid material in the form of a filament is extruded with the help of an extruder and melted and then the printhead deposits the melted material, through a nozzle, onto a build platform. Commonly, the nozzle moves in an X-Y direction to traces out the geometry of the design and deposits one layer worth of material. After this, the build platform moves down in the Z-direction. The distance equivalent to one layer height and the deposition resumes for the second layer. This entire process repeats and continues until the complete object is formed." [2]

The significant advantage of the technology is that range of the materials is increasing due to the possibility to form new materials in filament form; therefore various thermoplastic biomaterials can be used in filament providing the opportunity of growth in the development of three-dimensional bioprinting.

"The major strength of FDM is in the range of materials and the effective mechanical properties of resulting parts made using this technology. Parts made using FDM are amongst the strongest for any polymer-based additive manufacturing process." (Gibson 157)

However, Kalaskar doubts the possibility of forming new materials because he believes that there is a risk of losing specific properties and difficulty in calibrating the printer.

"Despite these benefits, the FDM technique includes restrictions in the input filament material properties and diametric size to feed it through the rollers and nozzle. Any changes in the properties of the material require a considerable effort to recalibrate the setting of the feeding parameters." (31).

The main drawback is that the technology implies a point vector construction that significantly affects the speed of production of various objects. Also, the part fabricated by the FDM process has dimensional inaccuracy compared to other additive techniques because of the variety of conflicting operation parameters. (Kalaskar 31).

Figure 12 shows the scheme of the FDM extrusion and deposition process.

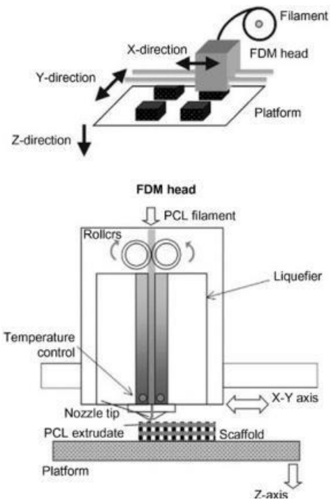

Figure 12. Scheme of the fused deposition modeling extrusion and deposition process. Adopted from Kalaskar (2017) "3D printing in medicine."

3.3.2 Multi Jet Modeling

The further extrusion-based system technology is Multi Jet Modeling that was initially developed for manufacturing high density metallic and ceramic components using low melting point alloys or a powder-binder mixture. Kalaskar describes this process as following:

"The material is loaded in a form or powder, pellet or bar and heated in a process chamber above the melting point of the binder, thus liquefying only the binder during the process. At this stage, the heated paste is pushed out through a heated jet nozzle and deposited onto a computer-controlled build table." (31).

The main benefit of this technology is the capability of building smooth and accurate components with highly comprehensive geometries at a relatively low-cost printer.

4 UTILIZATION OF 3D PRINTERS IN VARIOUS FIELDS

4.1 3D printing of food

Printing food is not a simple thing. It is complicated and resource-intensive technology because the whole food-extrusion chain has to be food-safe. Chocolate has similar properties as thermoplastics, other products can be extruded as a gel, and other ones can be sprayed as a liquid using a “sprinkling” type of system. The Dovetailed design studio in England invented one of these three-dimensional devices. Figure 13 demonstrates a printer that can create a raspberry by the food piece droplet by droplet.

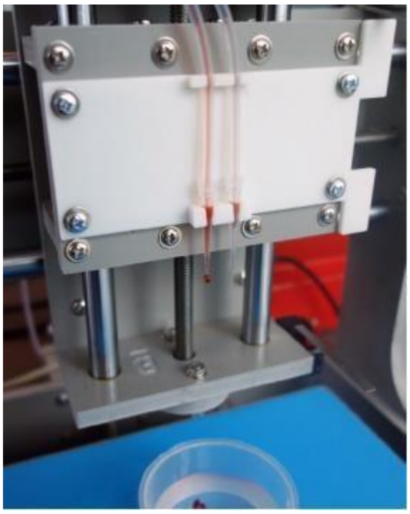

Figure 13. The “fruit” 3D printer. Adopted from Horvath (2014) “Mastering 3D printing.”

“It takes tiny drops of a fruit juice mixed with a gelling solution like sodium alginate. This mix is dripped into a liquid solution to make thin-skinned droplets using a molecular gastronomy technique called spherification.” (Horvath 179).

Despite the complexity of technology, there is a considerable demand for printing pancakes, pizza, chocolate, and lots of other types of foods.

4.2 3D printing in the automotive industry

3D printing technology plays a crucial role in the automotive industry, and additive manufacturing is increasing with every new year in that sector.

According to 3D printing industry.com: *"The recent advances in additive manufacturing, allowing for newer designs, reduced lead times, and decreased costs, are already paving the way for novel ways of conceiving and producing motor vehicles.*" [21]

Traditional manufacturing of rare complex parts in the automotive industry is very costly, compared to 3D printing technology, that is advantageous, inexpensive, and efficient.

An extra benefit of the additive manufacturing process is that it provides greater design freedom if a component needs to handle multiple functions, for example, current or cooling.

3D printing industry.com states that

"Creating complex metal lattice structures with Selective Laser Melting (SLM), engineers on the FLAC project aim to reduce the weight of components by decreasing their density. SLM technology could also improve their performance in contrast to traditional subtractive manufacturing processes. By structuring the components in layers, the process allows for more complex lattice structures, such as hollow ducts for airflow." [21]

4.3 3D printing in aerospace

The aerospace industry is proliferating. Three-dimensional printing has a significant impact on it. The aerospace industry includes several various departments that manufacture, research, and maintain the aircraft. 3D printing is widely used in the airline industry for both manufacturing end-use parts and prototyping. Airlines depend on 3D printing to facilitate supply chain constraints and reduce the number of wasted materials from traditional manufacturing processes. Saving enormous amounts of space and minimizing the weight of different parts of aviation is a major aim of aerospace manufacturing companies because it economizes money, time, and affects an aircraft's payload as well as emissions and safety. Unfortunately, traditional methods cannot provide such benefits as 3D printing technology, that can create a part using fused deposition modeling from the base up layer-by-layer.

Blog trimech.com states that *"Adding the material rather than removing it, reduces waste during manufacturing. Air ducts, wall panels, seat frameworks, and even engine components have all benefited from reduced weight enabled by 3D printing.*" [15] The technology has found a niche in aircraft manufacturing; for instance, the air company "Finnair" has used 3D printing for small-batch manufacturing.

4.4 3D printing in the architecture industry

Architecture is one of the important and high demanded areas where 3D printing is making a significant breakthrough. This cost-effective, developing technology will allow people to build cheap houses and various other unique buildings. Architecture often involves many resources such as human resources, various sophisticated equipment, and elaborate designs of impressive structures. Three-dimensional printers help to build structures most effectively. 2D drawings do not illustrate much about how an end structure will be shown. That is why architects use artist's impressions and 3D models to illustrate their creations. Nowadays, thanks to the advancement of 3D printing technologies, this process has become and continues to get more straightforward, cheaper, and faster.

According to 3D insider.com: *"Australian researchers think this is going to bring a lot of unique advantages to housing markets around the world. There is still a lot of experimentation going on with building structures right now, but it is only a matter of time.*" [5]

5 TYPES OF TECHNOLOGIES USED IN 3D PRINTING IN MEDICINE

5.1 Bioprinting techniques

Bioprinting works in the same way as conventional 3D printing, but instead of thermoplastics or other material, bioink is used, which consists of living cells. Artificial tissue imitating real tissue is created layer by layer until it is completely done. The expansion of using such technology in every branch of industry has resulted in the vast majority of bioprinters in the medical field. At present time, three-dimensional bioprinting is in demand in that field. Medical devices-network.com states that

"Rather than printing using plastic or metal, bioprinters use a computer-guided pipette to layer living cells, referred to as bio-ink, on top of one another to create artificial living tissue in a laboratory. These tissue constructs or organoids can be used for medical research as they mimic organs on a miniature scale. They are also being trialed as cheaper alternatives to human organ transplants." [12]

Medical laboratory Organovo based in the United States currently is experimenting with printing liver and intestinal tissue to help with the learning of organs in vitro, and with drug development for certain diseases. [12]

5.1.1 Laser-assisted bioprinting

Laser-assisted bioprinting is one of the most popular and modern bioprinting technologies. It allows individual printing cells for tissues with extraordinary accuracy and high resolution. According to Visscher et al.: *"Laser-assisted bioprinting technology is based on laser-induced forward transfer (LIFT) and enables the precise printing of individual cells in small constructs. Highly organized craniofacial tissues such as muscle may benefit from LAB technology by generating individual tissue units that can later be assembled into functional tissues using self-assembly or rational design"* (702). The scheme of Laser-assisted bioprinting is illustrated in Figure 14

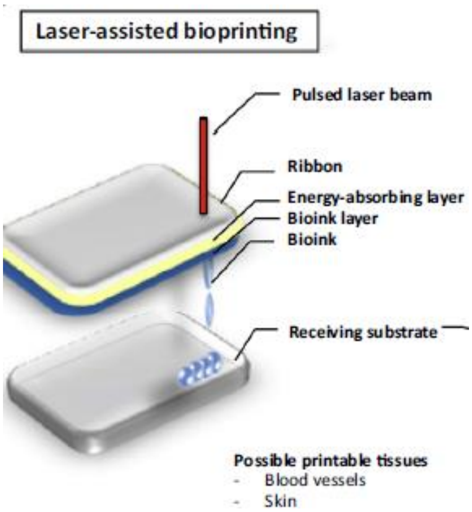

Figure 14 Laser-assisted bioprinting. Adopted from Visscher et al. (2016) "Trends in Biotechnology."

The main advantage of that technology is the ability to print small droplets with very high resolution. Moreover, it is possible to print high cell densities and highly viscous hydrogels. Currently, LaB is extensively used to print tissue constructs. (Kalaskar 124)

However, Visscher et al. note a number of shortcomings of this technology and worries about slowing down the development of this technology: *"The major drawbacks of LAB technology are the high costs involved in the printing process and the low flow rates due to the rapid gelation of hydrogels after deposition. These drawbacks may explain the lack of advances in this technology.". (703)*

5.1.2 Inkjet-based bioprinting

Inkjet 3D printers are promising bioprinting technology. The principle of work is similar to the usual printer, but the technology implies contactless layer-by-layer printing of 3D objects. According to Kalaskar:

"It is a non-contact technique that prints the 3D constructs layer-by-layer by depositing controlled volumes of liquid or ink and delivering them to predefined locations on successive layers. It is a useful method for depositing proteins or multiple cells in very small droplets onto a previously targeted spatial position." (124).

Visscher et al. note that skull and bone cells have been printed using this method, but he has to emphasize that the technology is imperfect because the material has to be in a liquid form to provide droplet formation. Therefore, the liquid must make a solid 3D structure with fundamental organization and functionality.

"Several craniofacial cell types, including bone cells, endothelial cells, cartilage cells, and muscle cells, have been printed in vitro using this technology. Unfortunately, the droplet viscosity that can be used in inkjet printers is low, which limits the thickness and ultimately, the mechanical strength that is required for structural support. As a result, inkjet printing technology is less applicable for load-bearing tissues in the craniofacial area, such as the mandible and temporomandibular joint (TMJ)." (Visscher et al. 703)

The main benefits are very high bandwidth, high resolution, and ease of use. It is noteworthy that commercially available ink jet printers can be modified for printing cells and biologics.

5.1.3 Extrusion-based bioprinting

Extrusion or micro-extrusion bioprinting is by far the most widely used technique. It is based on the technology of Fused Deposition Modeling printing comprising a syringe, nozzle, and pressure system. Kalaskar describes that technique as:

"Prior to printing with this technique, cells or proteins encapsulated in hydrogels, copolymers, or cell spheroids are loaded into sterilized syringes holding a micronozzle. As directed by the CAD software, beads of material are deposited in two dimensions; the stage or microextrusion head is moved along the z-axis, and the deposited layer serves as a foundation for the next layer." (125).

This technology enables direct printing of bone and facial tissues according to the individual requirements of the patient. Moreover, a wide range of printing biomaterials and inexpensive equipment are among the advantages of this printing technology.

"Microextrusion technology can be very useful for the printing of mechanically strong, patient-tailored polymeric constructs for craniofacial reconstruction that can be directly incorporated in the patient e.g., to treat bony fragments." (Visscher et al. 704).

The main benefit of such technology is the opportunity to deposit very high cell densities. There are some drawbacks, such as low print resolution and speed. (Kalaskar 125).

5.2 3D bioprinting in practice

5.2.1 3D bioprinting in vitro

At present, the research on the development of 3D in vitro cardiotextiles is focused on seeding cells from above or encapsulating them into hydrogel scaffolds.

The scaffold is made of plastic, and biodegradable materials, and cells are added to it. Scientists widely use scaffolding due to its simple construction and good bioprinting. Dr. Gabor Forgacs developed new scaffold-free technology. The principle of operation is that cells encapsulated in the hydrogel and were used to create tissue blocks with unique geometric design to simulate the target tissue or organ. Dana Akilbekova and Damel Mektepbayeva from Nazarbayev University, Astana interpret this process as:

"They clustered cells into spheroids and glued them together using biopaper made from hydrogel to print 3D blood vessels. Experimental blood vessels have been bioprinted using bio ink spheroids comprised of an aggregate mix of endothelial, smooth muscle, and fibroblast cells. Once placed in position by the printing head, the endothelial cells migrate to the inside of the printed blood vessel, the smooth muscle cells move to the middle, and the fibroblasts migrate to the outside." (95).

Figure 15 demonstrates an example of a printed segment of the vascular tree, using scaffold-free technology.

Figure 15. The printed segment of a vascular tree. Adopted from Akilbekova and Mektepbayeva (2017) "3D printing in medicine"

So last but not least possibility of 3D bioprinting to grow a human artificial ear using patients own stem cells. The operation starts with sketching a 3D-printed polymer and printing the mold of an ear, adding the collagen gel and implanted by stem cells removed from the fat. As these stem cells differentiate into cartilage, polymeric scaffolds decompose, leaving a full ear of mature cartilage cells. Akilbekova and Mektepbayeva describe that process as following:

"The process starts with designing the mold, printing it, injecting the gel made of collagen and bovine auricular chondrocytes, trimming the ear and incubating it in cell culture media. Producing structures out of cartilage has great prospects, as they do not need to be vascularized with a blood supply. Biomechanical and histologic analysis demonstrated close mimicry to the native auricle." (97-98).

5.2.2 In situ 3D bioprinting directly to defect site

Despite the enormous progress in 3D printing technology, recreating a fully functional organ with an elementary structure is still a challenge.

A new way of printing massive vascularized organs via direct in situ printing to the defect site was invented by Weiss in 2007. The idea was to use a new inkjet printing technology. The authors exploit 3D printing of stem cells to treat full-thickness skin wounds in mice. Akilbekova and Mektepbayeva describe this process as: *"Several layers of fibrinogen/collagen and thrombin were deposited and then equal amount of bio inks were printed per wound. Additionally, control wounds were treated with only* *gel. Wound closure, re-epithelization, and blood vessels density notably increased for cell treated wounds compared to the only gel treated wound"* (98).

Besides, scientists have used 3D laser printing technology to reconstruct a critical-size mouse's calvar defect on site. Several male mice with bone defects of 4 mm wide were placed in the 3D bioprinting system for in situ printing. Nanohydroxyapatite material was applied layer by layer to the site of the injury. This operation was successful, and most mice recovered without inflammation or other defects. Later, the defect sites were tested with X-ray microtomography, and the results showed that mature bone tissue was present in the defect sites. (Akilbekova and Mektepbayeva 98-99)

However, this method can also be used in the case of more severe calamitous and craniofacial injuries but requires appropriate vascularization and structural support.

Even though in situ 3D bioprinting is only tested in mice, hopefully, in the near future it can work on humans leading to great possibilities. Akilbekova and Mektepbayeva define several advantages of such technology:

"Scaffolds will be printed directly into the defect site and therefore avoiding the time-consuming stage of scaffold preparation and the risks related to contamination. Stem cells will be printed in situ and will be exposed to the natural environment and therefore can differentiate into required cell lineage without any in vitro manipulations. Additionally, in situ printing provides better control over standard or unexpected defects during the surgery." (102).

5.3 Patient specific medical devices

The rapid development of 3D printing technology has made an enormous variety of individual implants a reality and the only way out for patients. Traditionally, medical devices and services are not available to every patient or are very expensive. Any medical device requires several clinical trials and approvals, and there is no guarantee that it will work for patients. Also, implant manufacturing can take a long time, while 3D printing technology takes hours to produce even better implants.

Prosthetics is the primary product application of 3D printing. Using a Magnetic Resonance Imaging (MRI) or Computerized Tomography (CT) prosthetic limbs of any complexity can be printed within a day. Patients with diseases of the musculoskeletal system have a great promise because of prosthetics technology, which allows printing massive, patient individual bone constructs and implants that integrate into the surrounding bone and include collagenous matrix elements. Inkjet-based printing and laser-induced forward transfer technologies make it possible to print osteogenic cells and hydrogels.

Customized scaffolds that mimic the growth of new bone tissue were developed by a group of scientists from Washington State University. Theoretically, that technology might be exploited in dental work and give a promise for patients who need medicine for treating osteoporosis. (Akilbekova and Mektepbayeva 102-103).

Patient's skull can be substituted by printed cranial implants and can be customized according to the patient CT or MRI scan. Moreover, there is a possibility of producing plastic implants that will have several advantages compared to traditionally used implants. This is an essential aspect because it saves time and money for patients and decreases the risk of infection and brain damage.

Making personalized dental implants is one of the earliest medical application of the 3D printing technology that generally used for the preparation of rapid prototypes, trial restorations, and dental crowns. Traditional method "subtractive process" has its shortcomings such as low precision, the opportunity of introducing tiny cracks and waste of the raw material. Additive manufacturing technology can significantly enhance the speed and quality of dental prostheses preparation process.

Figure 16 illustrates the process of titanium implant placement.

Figure 16. Implant placement. Adopted from Akilbekova and Mektepbayeva (2017) "3D printing in medicine."

6 FUTURE OF 3D PRINTING

This chapter is aimed to describe the probable future of 3D printing technology, its influence on people's lives, and the search for new applications. A 3D printer is a real multifunctional factory, small and compact. At the expense of it, the future of 3D printing quite definitely can be prosperous.

6.1 Pharmacy

Recently, 3D printing technology allows creating personal pills and medicines by printing them on a three-dimensional printer. Such pills and medicines can gradually improve the effectiveness of traditional medicines because they have special dosage dispensers for individual doses of medicine or slowly soluble capsules that gradually inject the right amount of medicine into the body. This approach will save patients from having to calculate their own portion of the medicine. According to all3dp.com:

"This could include integrating multiple patient-specific drugs into a single form as well as adjusting the rates at which various medications dissolve." [19]

An interesting form of the capsule will be unusual for children who often do not want to take medicines. Parents task will only be to make sure that the child does not get carried away with the process and does not eat too many treatment capsules at once. This problem can also be solved with the help of a particular safe dispenser for medicines, which gives out a specific income at a time and does it clearly at given the time of day, issuing the appropriate reminder signal. [16]

Figure 17 illustrates the example of pills with an image produced with the help of 3D printing technology.

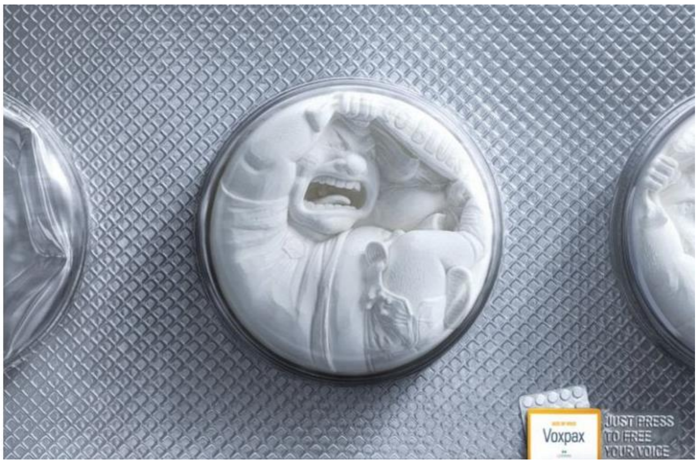

Figure 17. 3D printed pill. Adopted from lifeglobe.net

6.2 4D printing

4D printing basically is an evolution of 3D printing technology. 3D printing implies creating objects in one particular shape, while 4D printing technology uses unique materials that can change their shape depending on particular conditions. According to tektonikamag.com: *"The key difference is that the 4D printing process uses a special material that can also be programmed to self-assemble and change its shape later on upon encountering heat, ice, water, movement, pressure, or a certain type of chemical."* [17]

Application for 4D printing is tremendously thrilling for example underground pipes that can "repair" themselves, after detecting a leakage or 4D print bricks that can modify itself to accommodate more or less stress on the wall.

Such technology is still in development by a group of researchers from MIT university, 3D printing manufacturer Stratasys, and 3D software company Autodesk. [20]

Figure 18 demonstrates the example of 4D printing material

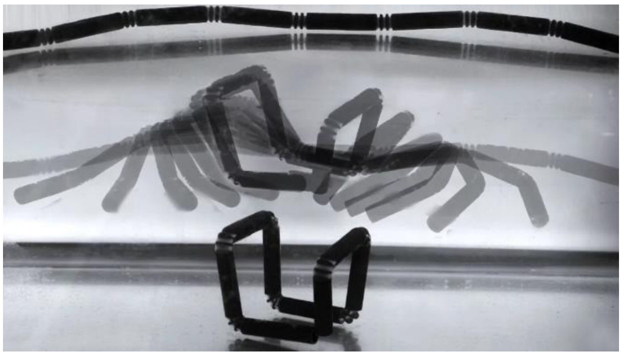

Figure 18. 4D printing experiment from MIT. Adopted from all3dp.com

Tektonikamag.com states that: *"4D printing still is a bleeding edge technology. 4D printers and the materials they use are expensive, so it will be a while before the world begins welcoming 4D-printed objects into offices and homes en masse."* [17]

7 CONCLUSION

In conclusion, it should be mentioned that three-dimensional printing technology is getting more demanded by people from various fields and industries. 3D printing is getting cheaper and develops new ideas for printing different products. It is fascinating to imagine how 3D printing will affect people's lives. It is possible to say with certainty that in a few years there will be significant changes in people's lives. Perhaps the 3D printing of organs and tissues will help to prolong the life of many people. Many diseases such as cancer can be defeated by literally replacing the affected organ with a new one printed with the help of a 3D printer. Thanks to this technology, human development will increase several times, and the goals that could be achieved in hundreds of years will be achieved within a decade. In the nearest future, almost every single product will be printed using that technology. Every family will have a 3D printer, and it will be a major and integral part of household appliances.

That bachelor's thesis aimed to examine the parts of 3D printer, its principle of operation, and how it utilized in medicine. The thesis is divided into two main parts - theoretical and practical one. The first part describes the parts of the printer and its operation as well as differences between individual technologies, its advantages and disadvantages. The first, most popular, as well as the latest technology developments, are described from the industrial, operational advantageous and disadvantageous point of view. The practical part is considered from the point of view of the possibility of using printers in various fields, including medicine.

8 LIST OF FIGURES

9 LIST OF ABBREVIATIONS

3D – Three-dimensional

SLA – Stereolithography

SLS - Selective laser sintering

FDM - Fused deposition modeling

MSL - Microstereolithography

DLP - Digital light projection

MJM - Multi Jet Modeling

UV – Ultraviolet

CAD - Computer-Aided Design

FFF - Fused Filament Fabrication

PET - Polyethylene terephthalate

LCD - Liquid crystal display

DMD - Digital micromirror device

DMLS - Direct metal laser sintering

DLF - Direct laser forming

SLM - Selective laser melting

EBM - Electron beam melting

AM – Additive manufacturing

LaB - Laser-assisted bioprinting

MRI - Magnetic Resonance Imaging

CT - Computerized Tomography

MIT - Massachusetts Institute of Technology

4D – Four-dimensional

10 LIST OF REFERENCES

[1] Akilbekova, Dana & Mektepbayeva, Damel. (2017). Patient specific in situ 3D printing. 10.1016/B978-0-08-100717-4.00004-1. p. 41, 42, 43, 44

[2] “A Comprehensive List of All 3D Printing Technologies”. Manufactur3dmag.com, 5 November 2018 https://manufactur3dmag.com/comprehensive-list-all-3d-printing-technologies/. Accessed 11 August 2019

[3] Bell Chares. Maintaining and troubleshooting your 3D printer. 2014. ISBN-13: 978-1- 4302-6809-3. p. 6.

[4] Brian Evans Practical 3D printers. 2012. ISBN-13: 978-1-4302-4392-2. p. 1, 3, 4, 5, 6

[5] Flynt. “The future of 3D printing for architecture.” 3dinsider.com, 16 February 2017 https://3dinsider.com/3d-printing-architecture. Accessed 13 December 2018

[6] Gibson Ian, Strucker Brent Strucker, David W. Rosen. Additive Manufacturing Technologies. Rapid Prototyping to Direct Digital Manufacturing. 2010. ISBN: 978-1-4419-1120-9. P.16, 143, 157.

[7] Greguríc Leo. “What is a DLP 3D Printer? – Simply Explained.” All3dp.com, 1 September 2018 https://all3dp.com/2/what-is-a-dlp-3d-printer-3d-printing-simply-explained/. Accessed 5 August 2019

[8] Grumezescu Alexandru Mihai. Nanobiomaterials in Soft Tissue Engineering. Applications of Nanobiomaterials. 2016. ISBN: 978-0-323-42865-1. p. 37

[9] Horvath Joan. Mastering 3D printing. 2014. ISBN-13: 978-1-4842-0026-1. p. 179.

[10] “How Selectvie Laser sintering Works.” Manufactur3dmag.com, 28 January 2018 https://manufactur3dmag.com/how-selective-laser-sintering-works/. Accessed 7 August 2019

[11] Kalasakar Dr. Deepak M. 3D printing in medicine. Institute of Orthopaedics and Musculoskeletal Science, University College London, Royal National Orthopaedic Hospital, United Kingdom, 2017. ISBN: 978-0-08-100717-4. p. 1, 2, 25, 26, 29, 31.

[12] Nawrat. “3D printing in the medical field: four major applications revolutionising the industry.” medicaldevice-network.com, 7 August 2017, https://www.medicaldevice- network.com/features/3d-printing-in-the-medical-field-applications. Accessed 13 December 2018.

[13] Poologasundarampillai, Gowsihan & Nommeots-Nomm, Amy. (2017). Materials for 3D printing in medicine. 10.1016/B978-0-08-100717-4.00002-8. p.35, 37

[14] Prudhvi Reddy “Digital Light Processing (DLP).” Think3d.in, 24 August 2016, https://www.think3d.in/digital-light-processing-dlp-3d-printing-service-india/. Accessed 4 August 2019.

[15] Schwartz. “How 3D printing is transforming the aerospace industry.” blog.trimech.com, 7 November 2017, https://blog.trimech.com/how-3d-printing-in-transforming-the-aerospace- industry. Accessed 13 December 2018
[16] Sweet. “The Future of Pharmacy: 3D printing of pills”. Lifeglobe.net, 25 September 2016. https://lifeglobe.net/entry/7530. Accessed 26 May 2019
[17] Rose de Fremery. “What is 4D printing technology?”. Tektonikamag.com, 14 February 2019. https://www.tektonikamag.com/index.php/2019/02/14/what-is-4d-printing-technology/. Accessed 27 May 2019.
[18] Visscher. Dafydd O. et. al “Trends in Biotechnology” (2016). p.702, 703, 704.
[19] Yeap. “The Future of 3D Printing – A Glimpse at the Next Generation.” All3dp.com, 1 March 2019. https://all3dp.com/2/future-of-3d-printing-a-glimpse-at-next-generation-making/. Accessed 26 May 2019
[20] Yeap. “The Future of 3D Printing – Technology on the Horizon. “All3dp.com, 17 March 2019. https://all3dp.com/2/the-future-of-3d-printing-technology-on-the-horizon/. Accessed May 2019
[21] Zahnd. “3D printing in the automotive industry.” 3dprintingindustry.com, 10 May 2018, https://3dprintingindustry.com/news/3d-printing-automotive-industry-3-13258410. Accessed 13 December 2018